# DIELECTRIC PROPERTIES OF SOME SOLID INSULATING MATERIALS AT 750 Mc/s

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**ABSTRACT** Dielectric constants and power factors of solid insulating materials like mica, mycalex, plexi glass etc., have been measured at 750 Mc/s Loss factors and power dissipated in watts in the materials have also been calculated from observed results. A resonant line oscillator, having tuned concentric lines in the filament circuit, has been constructed for the purpose The detector, which is also of the resonant line type, has been constructed for voltage measurement.

## INTRODUCTION

A considerable amount of work has been carried out by different workers in an endeavour to clarify the behaviour of solid insulating materials under alternating electric stress. When a solid material is subjected to ultra high frequency electric stress, various factors become operative within the body of the material depending on its physical and chemical complexities. This makes an understanding of the dielectric behaviour of solid insulating materials under high frequency stress, a difficult matter. The use of any material for the purpose of u.h.f. work presupposes a knowledge of the dielectric constant $\epsilon$ and conductivity of the substance at the particular frequency region. Conductivity for insulating materials varies widely at different frequencies and is controlled largely by the same molecular or ionic processes which determine the dielectric constant. So, in selecting any material for service at cm waves, both dielectric constant and conductivity should be considered together. The conductance phenomenon can be studied by measuring the loss-tangent (tan $\delta$) of the substance.

A number of theories have been postulated to explain dielectric absorption and associated behaviour of dielectrics subjected to a.c. fields. Most significant amongst them are the inhomogeneity theory of Maxwell, extended by Wagner (1914), and the theory of polar molecular orientation by Debye (1929). Debye's theory provides well the necessary explanation for the observed dielectric behaviour of gases and especially liquids. The rotation of dipoles in a viscous medium gives rise to frictional heat loss, expressed as power factor, and also to a contribution to dielectric constant which vanishes when the dipoles are prevented from responding by too great viscosity or too high frequencies. This explanation may be accepted as correct for the case of liquids but is difficult of immediate acceptance in the case of solid insulating materials as it is extremely difficult to attach a meaning to the term viscosity in the case of solids. An attempt to extend the dipole theory in the case of amorphous solids has been made by Gemant (1935). The conception of 'relaxing elasticity,' which is originally due to Maxwell, has been introduced by Gemant to explain the behaviour of solid bodies. But no complete theoretical explanation is as yet available for explaining the behaviour of solids under the influence of a.c. fields. Most of the important insulating materials are solids. Materials like ebonite, bakelite, mycalex, etc., are polyphasic systems containing some components in a microcrystalline form, others in the amorphous state. The experimental investigation, on the behaviour of solid insulating materials under h. f. electric stress, should therefore be continued in order to assist the eventual development of a satisfactory theory. A study of dielectric constant and loss factor, especially, at ultra high frequencies is essentially important, in view of the fact, that the subject of u. h. f. has gained considerable importance, in recent years, in its application to almost every branch of science. Construction of u. h. f. equipments and finally their efficient operation depends to a great extent on the evolution and commercial utilisation of various loss-free materials.

## THEORETICAL

*Dielectric Constant.*—Dielectric constant has been determined by adopting a modification of Drude's (1895) Lecher wire method. Instead of, immersing the whole Lecher wire, in the dielectric as has been done by Drude, insulating materials in the form of thin slabs are interposed between the indicator at the sending end and the shorting bridge, so that the Lecher wire system immersed in an air-dielectric-air medium.

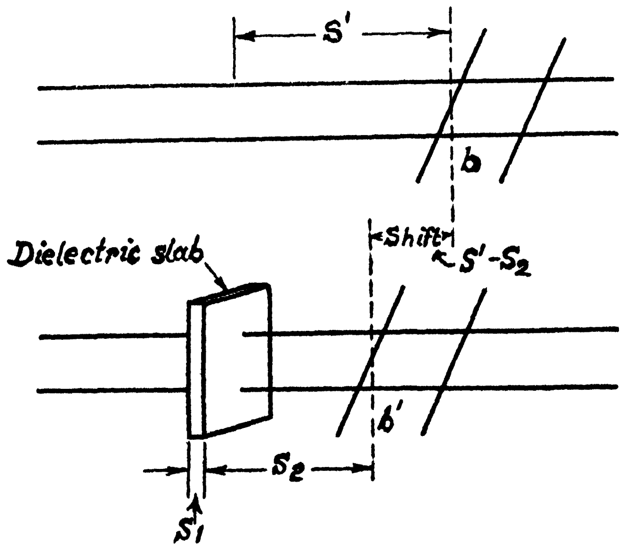


FIG. 1

In figure 1 $b$ indicates the position of the short circuiting bridge for resonance, in case the Lecher wire is completely immersed in air, the position of the bridge is to be moved to $b'$ in order to restore resonance, when the slab is interposed between the indicator and the bridge. If the slab is moved from this position on either side, the resonance is disturbed and the bridge requires shifting to a new position to restore resonance. If the slab is moved gradually, and for each position the bridge shift is measured, the position of the slab for maximum bridge shift can be found. An expression for the refractive index $n$ of the material in terms of the maximum bridge shift, the thickness of the slab ($S_1$) and wavelength of excitation ($\lambda$) has been deduced (King, 1937) to be

$$\tan\frac{\pi}{\lambda}(\text{Max. bridge shift}+S_1)=n\tan\frac{\pi n S_1}{\lambda} \qquad \ldots \quad (1)$$

In the region of cm waves, the refractive index may be considered to be equal to the square root of the dielectric constant. So eqn. (1) may be written as

$$\tan\frac{\pi}{\lambda}(\text{Max. shift}+S_1)=\sqrt{\epsilon}.\tan\frac{\pi S_1}{\lambda}.\sqrt{\epsilon} \qquad \ldots \quad (2)$$

Hence, the experiment consists of finding the maximum bridge shift at a particular frequency and measuring the thickness of the material to find the dielectric constant.

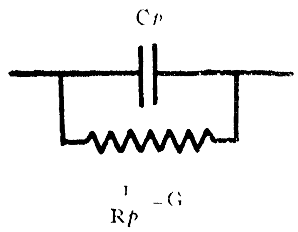


FIG. 2

*Loss Angle*.—The insulating slab may be represented (Fig. 2) as a parallel combination of capacitance and resistance. The admittance of the combination may be written as

$$Y = G + jB$$

where G and B represent conductance and susceptance of the material respectively. The power dissipated in the material under the influence of h. f. electric field is due to both conductance current and displacement current and may be expressed as

$$P = V^2.C_p.\omega.\tan\delta$$

where $C_p\omega$ is the susceptance of the material. So the loss tangent can be written as

$$\tan\delta = \frac{1}{R_p.C_p.\omega} = \frac{G}{C_p.\omega}. \qquad \ldots \quad (3)$$

For a parallel wire transmission line of length $l$ and propagation constant $\gamma$ and terminated by impedances $Z_t$ and $Z_r$, at the transmitting and the receiving end of the line, the impedance $Z_x$ at any point $x$ from the transmitting end of the line can be deduced to be

$$Z_x = \frac{\left\{ \sinh \gamma(l-x) + \frac{Z_r . \gamma}{Lp + R} . \cosh \gamma\,(l-x) \right\}}{\frac{\gamma}{Lp+R}\left\{ \cosh \gamma(l-x) + \frac{Z_r . \gamma}{Lp+R} . \sinh \gamma(l-x) \right\}}$$

where L, R, represent the inductance and resistance per unit length of the line respectively and $p$ represents the Heaviside differential operator. The above expression of impedance may be written as

$$Z_x = \frac{Z_0 Y_r . \sinh \gamma(l-x) + \cosh \gamma(l-x)}{\frac{1}{Z_0}\left\{ Z_0 Y_r \cosh \gamma(l-x) + \sinh \gamma(l-x) \right\}}$$

where $Z_0$ is the characteristic impedance, and

$$Y_r = \frac{1}{Z_r}$$

when $x=0$, the input admittance of the line (Y), completely immersed in air, can be written to be

$$Y = \frac{1}{Z_0} \frac{Z_0 Y_r . \cosh \gamma l + \sinh \gamma l}{Z_0 Y_r \sinh \gamma l + \cosh \gamma l} \qquad \ldots \quad (4)$$

For a terminating link of zero impedance, the input admittance of the parallel wire, immersed in air (Eq. 4) may be written as

$$Y = \frac{1}{Z_0} \coth \gamma l .$$

After the material is inserted the total admittance of the system becomes

$$Y = G + jB + \frac{1}{Z_0} \coth \gamma l$$

$$\simeq G + j(B - \frac{1}{Z_0} \cot \beta l)$$

neglecting the attenuation constant compared to phase constant,

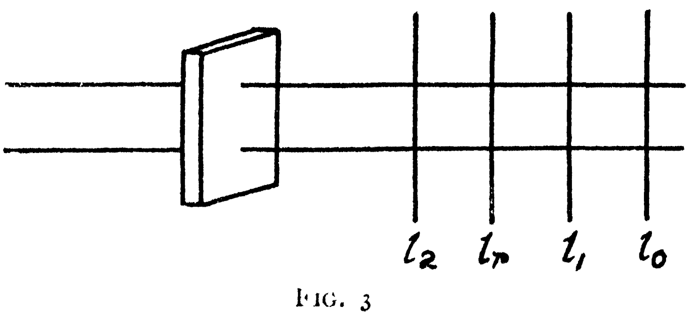


FIG. 3

If (Fig. 3) $l_0$ is the length of the Lecher wire at resonance when it is solely immersed in air and $l_r$ is the length at resonance when the slab is interposed, it can be shown that

$$B = \frac{1}{Z_0} \tan \frac{2\pi}{\lambda} (l_0 - l_r) \qquad \ldots \quad (5)$$

and
$$G = \frac{1}{Z_0 \sqrt{q-1}} \left\{ \tan \frac{2\pi}{\lambda}(l_0 - l_r) - \tan \frac{2\pi}{\lambda}\left( l_0 - l_r - \frac{l_1 - l_2}{2} \right) \right\} \qquad \ldots \quad (6)$$

where $l_1$ and $l_2$ are the lengths so that

$$\left| \frac{V^2_m}{V^2} \right| = q$$

where, $V_m$ is the voltage developed at the test object at resonance and V is the voltage developed at the test object for any position of the bridge other than resonance.

The resonant line voltmeter, described under experimental head, may be considered as a square law detector. So, if $I_m$ and I represent the change in the plate current of the detector, corresponding to $V_m$ and V, then

$$\frac{I_m}{I} = \left| \frac{V^2_m}{V^2} \right| = q$$

From Eqns. (3), (5) and (6),

$$\tan \delta = \frac{G}{C_p\omega} = \frac{1}{\sqrt{q-1}} \cdot \left\{ 1 - \frac{\tan \frac{2\pi}{\lambda}\left( l_0 - l_r - \frac{l_1 - l_2}{2} \right)}{\tan \frac{2\pi}{\lambda}(l_0 - l_r)} \right\}$$

If $I_m = 2I$, the above expression reduces to

$$\tan \delta = 1 - \frac{\tan \frac{2\pi}{\lambda}\left( l_0 - l_r - \frac{l_1 - l_2}{2} \right)}{\tan \frac{2\pi}{\lambda}(l_0 - l_r)} \qquad \ldots \quad (7)$$

So, the experimental method of determining loss tangent involves the determination of bridge shift $(l_0 - l_r)$ and also half the width $\left( \frac{l_1 - l_2}{2} \right)$ of the resonance curve where $I_m/I$ equals $q$.

## EXPERIMENTAL EQUIPMENTS

*Oscillator.*—The circuit diagram of the oscillator using 316-A tube is shown in Fig. 4. For efficient operation of the oscillator, tuning in the form of adjustable concentric lines, have been provided in each of the filament leg of 316-A. The concentric lines consist of copper tubes, silvered inside of bore diameter ½″, outer diameter 5/8″ and length 16″ with a solid silvered brass rod of diameter $\frac{1}{4}''$ and length $16''$, placed coaxially. One end of the rod is soldered with a metal plug to one end of the outer tube. The other end

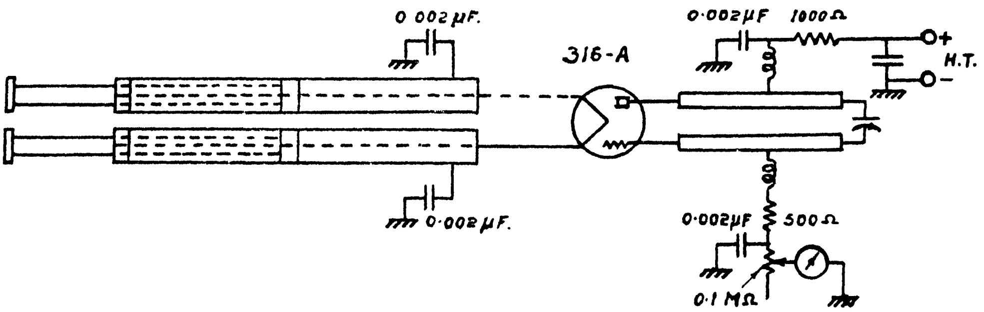


FIG. 4

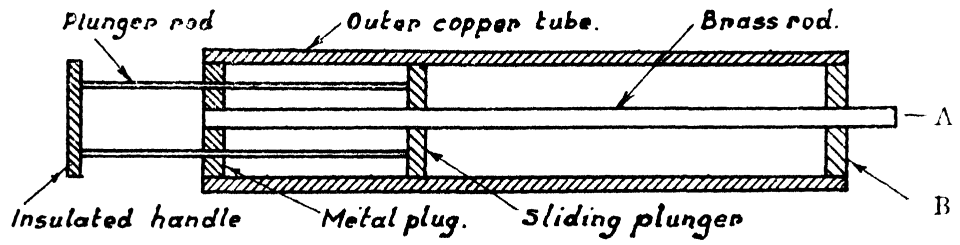


FIG. 4A.

A—To Filament, B—Insulated bushing.

of the inner conductor passes through an insulated bushing and directly connected to filament leg. For optimum operation, length of each of the filament tuned line, should be about one quarter wavelength. The length can be adjusted, at each frequency of operation, by means of, a close fitting metal plug, which makes good contact, between the inside wall of the outer tube and the rod, and which can be smoothly shifted by means of a plunger. The construction of the filament tuning stub is shown in Fig. 4A. The resonant lines between plate and grid consists of two tubes of diameter $\frac{1}{8}''$ and length $2\frac{1}{8}''$, with a small trimmer at the end for changing the frequency. The r. f. chokes on the plate and grid circuit, consisting of 15 turns of 32 B & S copper wire and of length $1\frac{1}{2}''$ wound on mycalex rod of $\frac{1}{4}''$ diameter have been found to be satisfactory. A sheet of copper, $2' \times 6'' \times 1/32''$, has been fixed underneath the bakelite chasis of oscillator to provide a reference ground and all the bypass condensers from the plate, grid and filament circuits have been directly connected to this reference gound.

The adjustment of the oscillator has been found to be critical, especially with respect to the filament tuning. For each wavelength, the filament stubs need adjustment. The two supporting bridges for these tuned lines are also adjustable, so that they are easily placed at the points of minimum r. f. voltage, in order that the power-loss due to dielectric absorption may be kept at a minimum value. The positions of plate and grid supply leads are also adjustable, so that they can be connected to nodal points, as far as practicable. All the adjustments are made at low plate supply voltage for maximum grid current and then the full plate supply voltage of 300 volts is applied.

The oscillator works over a range of 40 cms to 50 cms wavelength. The oscillator is coupled loosely to the Lecher wire system and is also screened by a copper box from the rest of the system, so that the detector may not be susceptible to direct pick-up.

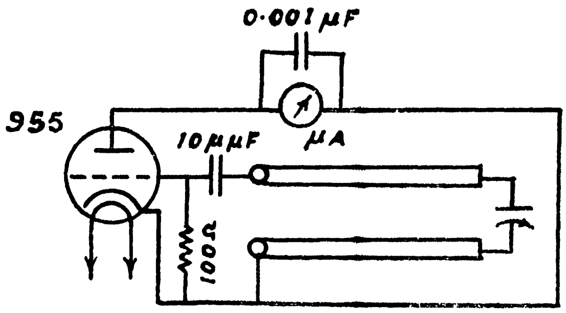


FIG. 5

*Detecting Device.*—The detecting device consists of a resonant line valve voltmeter using 955 (Fig. 5). The two resonant lines connected between grid and cathode consists of two silvered copper tubes of diameter 1/8″ and length 2″. The trimmer shunted at the end of resonant lines is meant for tuning.

The experimental arrangement is shown in Fig. 6. For power-factor measurement, the insulating slab is placed at a voltage antinode, next to the short circuiting bridge, so that the line impedance at the position of the slab is practically infinite. The valve voltmeter fixed at right angles to the Lecher wire and placed on a movable truck is placed near the voltage antinode, next to that of the slab. This arrangement reduces to minimum the

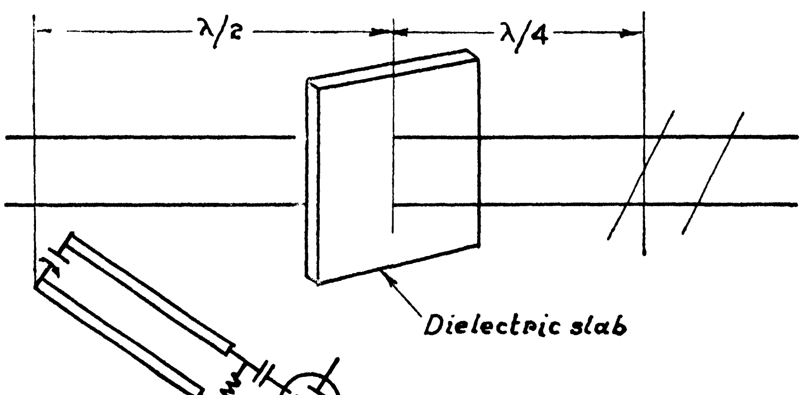


FIG. 6

loading effect on the main circuit and hence improves the accuracy of the determination of bridge positions. Moreover, the voltage measurement is not affected, as the half wavelengths long line, between the voltmeter and the slab, if assumed to have negligible attenuation, may be regarded as an unity ratio transformer. The short circuiting bridge is of tandem type.

## RESULTS AND DISCUSSION

Table I shows the values of $\epsilon$ and $\tan\delta$ for four different materials as obtained experimentally. The expression (2) for dielectric constant is a transcendental equation. To calculate the values of $\epsilon$, Newtonian approximation Sanden and Jahnke's table have been used.

TABLE I

Frequency = 750 Mc/s

| Material | Thickness ($S_1$) (cms) | $(l_0 - l)$ (cms) | $\left(\frac{l_1 - l_2}{2}\right)$ (cms) | $q$. | $\epsilon$ | $\tan\delta$ |
|---|---|---|---|---|---|---|
| Mycalex | 0.07 | 3.0 | 0.2 | 1.8 | 4.2 | .08 |
| Plexiglass | 0.64 | 1.0 | 0.1 | 2 | 2.6 | .02 |
| Mica (Brown) | 0.63 | 2.0 | 0.15 | 2 | 4.2 | .07 |
| Ebonite ... | 1.25 | 2.0 | 0.2 | 1.63 | 2.6 | 0.12 |

The power loss per unit volume of a dielectric is equal to $2\pi f E^2 \times 0.2244 \times 10^{-12}$. watts per cu.

This may be written in this case as $= 106 \times 10^{-5} . E^2 . \epsilon\tau$ ... (8)

where $f$ = Frequency in c.p.s. $= 750 \times 10^6$ c.p.s.

$E$ = Voltage gradient in dielectric (r.m.s. voltage per in.)

$\tau$ = Power factor of the dielectric which may be taken as $\tan\delta$.

To measure the voltage gradient (E), the valve voltmeter is calibrated by means of a G. R. oscillator, type 857-A, and a thermocouple microammeter combination at 500 Mc/s, and the result involving plate current change and input voltage is plotted as shown in Fig. 7. The voltage gradient has been found from the change in plate current at resonance ($I_m$), spacing between Lecher wire and the curves in Fig. 7. From Table I and eqn. (8), power loss in watts for different materials have been calculated and given in Table II.

The rate at which heat is generated in a dielectric is proportional to $\epsilon\tau$, which is termed the loss factor of the dielectric. The loss factor is the best single criterion for the ability of a solid insulating material to withstand high r. f. voltages. From the above two Tables, it may be remarked that plexi

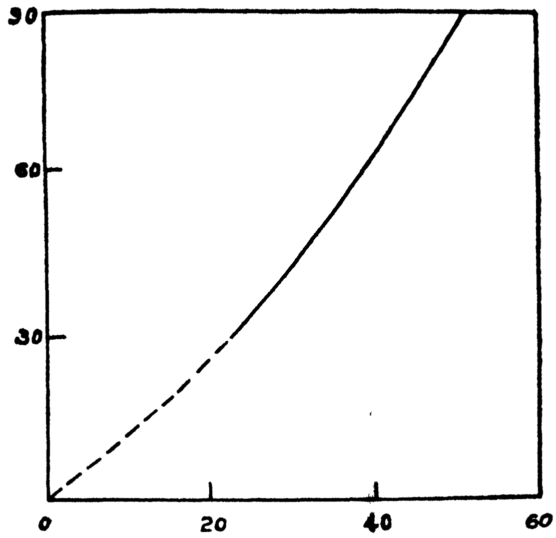


FIG. 7

TABLE II

Frequency = 750 Mc/s

Spacing between Lecher wire = 1 5″

| Material | $I_m$ μA | E Volts/in | Power loss in watts/cu. in. | Loss factor τ. ε. |
|---|---|---|---|---|
| Mycalex ... ... . | 60 | 24 | .21 | 0.34 |
| Plexi-glass ... ... | 72 | 30 | .05 | 0.05 |
| Mica (Brown) .. ... | 60 | 24 | .18 | 0.29 |
| Ebonite ... ... . | 65 | 26 | .22 | 0 31 |

glass and mica, having lower loss, are more suitable for work like valve bases, insulating supports, coil formers etc., whereas mycalex and mica may be used for such work as necessitates insulating materials of high dielectric constants.

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